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Input Data for Fire Modeling

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ABSTRACT

Reliable burn data are needed as inputs for fire models, for use as well as for model validation. To this end, a set of five merchandise kiosks have been burned, and the results carefully analyzed. A number of conclusions emerge, many of them of a cautionary nature. Perhaps the most important ones are that (a) The results of apparently identical fires can differ substantially; it follows that a number of runs must be made to get statistically significant results. (b) the "raw" data <u>must</u> be analyzed and rationalized. (c) the time delay for the O_2 analyzer is variable, not constant. Suggestions are made for further work.

INTRODUCTION

In order to get information and insight as to how a fire spreads on furniture or other items, many test burns have been carried out (refs. [1]-[4]). These have yielded the history of the rate of heat release, the production of CO, CO_2, soot and smoke, and other interesting data. The rate of heat release (RHR) is the most useful indicator of the impact of a fire [1]. These data are important for fire protection engineers in order to make rational decisions on risk, for manufacturers to know what materials to use, and in order to get data for verification of room-fire models and/or as input to such models (see [5]-[10]). The present study adds to that data base. These data are to be included in a large data base in FDMS format [11].

It was decided to examine merchandise kiosks (booths); they are now found everywhere, indoors as well as outdoors; in malls, cinemas, etc. No one has, at present, any quantitative knowledge of how these burn. Five burns were carried out: three ostensibly identical open-air burns with the kiosk opened up (these serve as a baseline), one burn with the kiosk closed up, and one with the kiosk open, but in a large enclosure.

Description of kiosk.

Fig.1 is a photograph of the kiosk we used, with the shelves down and merchandise placed on it. With the hinged shelves <u>up</u> (that is, the kiosk closed, as for the evening), it is 1.2 m square, and 2.1 m high. The bottom part is essentially a box, with two hinged doors in front to permit access to the interior. The doors in the underside of the kiosk were kept slightly open. The top surface of the box serves as the counter-top. There are columns at each corner, which support a light superstructure. The interior of the box principally serves for storage of inventory; it also contains electric cables for lights, heat, etc. We have assumed that cotton Tee shirts are on display. Three cardboard boxes which contain excess inventory are placed under the counter (inside the box).

Ignition

It is assumed that ignition would occur only through a concatenation of two accidents: first, some defect in the electric lines produces sparking or arcing. Second, the shipping/storage boxes under the counter (inside the box) are not pushed all the way in, preventing the door(s) from closing completely; this provides for the ventilation, which is essential. The short in the cable is simulated with a modified electric heat tape. The tip of the tape is placed between the two rear boxes; it reliably produces a flame 7 to 8 cm high at the tip whenever power is applied.

The series of photographs of test 2 shown in the talk help to visualize and understand the progress of the fires in the open. The kiosk collapsed at t = 1500 s. The weight measurements are useless after the collapse, and the test was discontinued at t $\approx$ 1660.

EXPERIMENTAL RESULTS

The heat release rate of kiosk 2, burning in the open, is shown in figure 2. Note that $\dot{Q}$ is limited to about 40 kW for the first 10 minutes. As we will show later, this is because the burn is ventilation-limited. There are several abrupt drops in the remaining mass, the last quasi-discontinuity being the largest (about 43 kg). These occur when pieces of the structure, such as the cabinet doors and the superstructure, fall, either on or off the weigh platform.

The mass-loss rate $\dot{m}(t)$ is found by making a running five-point polynomial fit to smooth the m(t) data, then taking the derivative at consecutive points. The places where there were sudden displacements of material are seen as sharp spikes, both positive and negative. These are irrelevant to the pyrolysis rate, and have been removed; the resulting mass loss rate curve is displayed in Figure 3.

The effective values of the heat of combustion, H_c, are obtained by dividing the values of the rate of heat release (RHR) by the pyrolysis rate (as represented by the mass loss rate $\dot{m}$):

$$H_c(t) \equiv \frac{\dot{Q}(t)}{-\dot{m}(t)} \qquad (1)$$

This is shown in Figure 4. The raw data, however, cannot be naively accepted as is: even though the spurious spikes in $\dot{m}$ were removed, spikes still appear in $H_c(t)$. The reason is inadequate time phasing between $\dot{m}$ and $\dot{Q}$. The correct phasing is found by associating real spikes in $\dot{m}$ and $\dot{Q}$; thus, the doors fall in at t $\approx$ 1600 s, producing a spike. There is an associated spike in $\dot{m}(t)$, but it occurs at t $\approx$ 1650. The resulting (spurious) spikes in H_c were removed, as were the remaining spikes, which were also spurious. The remaining curve has been fitted with a non-linear least-squares fit, as shown. The results for kiosks 3 and 4 are similar.

The fact that H_c starts at low values is intriguing -- it probably reflects very incomplete combustion in the early stages. This is consistent with the large amount of white smoke which was apparent early on. The radiative heat fluxes from the flames from kiosk 2 are shown in Figure 5.

To summarize: as time goes on, the fire becomes stronger, in the three "standard" tests. This is in part due to the overhanging shelf beginning to burn on the underside; partly, too, the fuel pyrolyzed from within the box, which does not get to burn on the inside, can burn outside. It does not do so at first, so that white smoke is visible, instead. Later, when there is flame outside the box, that flame pilots the fuel, so that the power output increases even more. When the doors fall off, internal flashover takes place in the box, and the power output goes much higher.

Comparisons

Runs 2 to 4 were ostensibly identical; figure 6 shows the three resulting HRR curves. The heat release rates are similar for the first 600 seconds or so. Moreover, it is clear that the **peak** outputs were about 1.8 MW. The greatest single *difference* among these curves lies in the time delays to the onset of serious burning -- a nine-minute difference. When the curves are shifted so that the first peaks overlap, the similarities are much more striking; see figure 7.

The effective heat of combustion curves should be more nearly a property of the kiosk, and hence more nearly identical to each other (except, possibly, for the scaling along the time axis). The comparison is best made with smoothed values (see figure 8). The results are similar in terms of the peaks and valleys and the general upward trend; indeed, the curves nearly overlap for the first 600 seconds. The difference between them beyond 600 s is, however, surprising.

Note that the mass-loss rate depends on the **pyrolysis** rate of the solids, whereas the rate of heat release depends on the **combustion rate**, which depends on other factors besides the fuel supply rate. Hence what we have identified as H_c is in fact a function which depends on the (instantaneous) combustion efficiency **as well as** the effective heat of combustion, so that the curves labeled "effective heat of combustion" really are of $\chi_A(t)H_c(t)$.

Attempts to correlate the peaks and valleys of $\chi_A(t)H_c(t)$ with easily recognizable events, such as the falling-off of the doors, was not successful. A possible alternative explanation is that perhaps the ignition and burning of different items, such as the boxes, the shirts, etc. produces these variations. It would be interesting to test out this hypothesis.

Finally, just as the rates of heat release all have similar peak values, so do the fluxes -- about 30 kW/m^2 for the lower gauge and about 35 kW/m^2 for the eye-level gauge.

Burning in different configurations

Test 5 was for the kiosk all closed up, as it would be for the night: the shelves are folded up, and all the shirts which are otherwise displayed during the day are stored in the three boxes underneath. In burns 2 to 4, the shelf just above the doors was the first "external" item to ignite; with this shelf folded up out of the way, there was some question as to whether the fire would ever grow beyond the ventilation-limited fire underneath. If it did, however, it would be expected that during a fire, these interior "walls" (consisting of folded-up shelves) would radiate to each other, as in a furnace, resulting in much faster evolution of pyrolysis products.

The results of this burn are shown in the following figures. Figure 9 shows the rate of heat release; the fire is seen to "take off" after t = 600 s, about the same time as the open-kiosk fires did; surprisingly, the shelf being out of the way made no difference. The expectation of a higher peak output, on the other hand, *is* borne out: the peak is 3.2 MW. The $\dot{m}(t)$ curve is similar, as would be expected.

Finally, we consider test 1, the kiosk burning in an enclosure; the enclosure that was built for these tests was 18'x18' and 12' high. The doorway height was 8' and its width 2 m. For this case, two thermocouple trees were included, one in the doorway and one in the back.

As expected, the fire initially progresses the same way as in tests 2-5. At t $\approx$ 26 min., the superstructure collapses; within 15 seconds, the fuel in the enclosure -- including the paper on the gypsum-board walls and ceiling -- is burning, and flashover begins; one can see flames emerging from the compartment. The fire was extinguished at this point, before it grew any greater.

The HRR curve is plotted on semi-logarithmic paper, to give equal weight to comparable fractional increases in power output; see figure 10. The curve shows several asymptotes, indicating several "stages" of burning. The first asymptote, at about 45 kW, corresponds to ventilation-limited burning inside the box. At t $\approx$ 750 s, there is renewed growth, apparently connected with ignition of material outside the box, to about 400 kW. At t $\approx$ 1100 s, there is another growth spurt, connected with the doors to the box falling out. The output then rapidly reaches a peak of 1.2 $\pm$ 0.2 MW, until the last stage, which is flashover.

The radiation flux to the eye-level gauge and that registered by the floor-level gauge follow very similar patterns. The peak values before flashover are about 20 and 5 kW/m^2, while at flashover, 185 and 36 kW/m^2, respectively.

ANALYSIS.

General observations. The fire is ventilation-limited so long as the box retains its integrity. The counter-top protects the shirts above it; indeed, the shirts which were hung in the center of the kiosk did not burn until 20 minutes into the burn, in test 2.

The **intrinsic replicability** of the basic test is of interest. The first peaks for the RHR curves are 1440 kW, 1519 kW, and 1757 kW for kiosks 2 to 4, respectively. These are insufficient data from which to draw statistical conclusions; however, if we merely average the highest and lowest values, then the first peak is 1600$\pm$160 kW; the second peak is 1407$\pm$22 kW, and the third peak is 1645$\pm$200 kW. The highest peak for a test was 1645$\pm$200 kW. The differences (or uncertainties) are of the order of 10%, a not uncommon value for large-scale tests. The *times of occurrence* of the peaks, however, vary by considerably more: the first peaks occur at t = 1086 s, 1218 s, and 1620 s, respectively. These differences are, most likely, attributable to slightly different vent openings in the three cases; as in hydrodynamics, a small cause has a large effect.

When the time axis for the RHR curve for kiosk 3 was shifted so that the peaks at 1200 s coincide, the spurious peak in H_c at 1200 was removed; however, another one at 1700 was then increased. This result appears to show that the delay time for the oxygen measurement is not constant. This effect has not heretofore been considered in the data analysis, but it is obvious if one thinks of it: the delay time between the probe and the oxygen analyzer is independent of the heat release rate; but when the HRR increases by an order of magnitude, even at a constant gas temperature, the gas velocity is ten times greater and therefore the time delay between flame and probe is cut by a factor of ten, decreasing the overall delay time. In the future, it should be straightforward to incorporate this correction into the data analysis.

Flashover

An expression for the minimum steady-state power output theoretically required to provide flashover in an enclosure with a given fire was given by Heskestad [12]:

$$\dot{Q} \approx 7.8 A_T + 378 A \sqrt{H} \tag{2}$$

where A is the vent area (assuming a single vent), H the enclosure height, and A_T its total area. For the enclosure under consideration, Eq.(2) yields $\dot{Q}_{min} = 4.0$ MW.

As we have seen, however, the peak power output in the open is 1.7 to 1.8 MW, nowhere near this minimum. Thus the fact that there was flashover in the compartment is a puzzle. Assuming 4 MW was achieved, it must have been because of:

(a) burning rate enhancement due to the radiative feedback from the room, plus

(b) the effect of paper burning off the gypsum-board walls and ceiling.

In order to estimate the feedback effect quantitatively, a dynamical room-fire model must be used, where the heat-flux feedback from the room to the burning object is explicitly taken into account. FIRST (see [13], [14]) is such a model. FIRST was run for a growing fire on a slab of material inside of a very large "room," to simulate the burning of the kiosk in the open. The dimensions and properties of the slab were so chosen that the power output peaks at 1700 kW, and runs out of fuel shortly afterwards. This same slab was then made to "burn" in an enclosure of the same size and venting as used in the test. The difference in output was surprisingly small: an increase, at the peak, of only 43 kW. This is certainly insufficient to trigger flashover.

On the other hand, suppose that the paper had ignited first. We can estimate its contribution to the RHR from work done by Nelson and Tu [15]. Careful measurement of the excess heat output due to the paper in an ASTM room lined by gypsum-board yielded about 68 MJ. This was released over a period of 75 seconds, yielding an average of 900 kW; if distributed as a triangle (a single peak), the peak would be 1.8 MW. The enclosure was considerably larger, and presumably would yield a higher peak. Conservatively, suppose that the paper in the present enclosure provided the same output; then, together with the 1.7 MW from the kiosk itself, this would result in a peak output of 3.5 MW -- still insufficient to trigger flashover.

Now reconsider the acceleration due to feedback. FIRST was run again, this time with an "equivalent" slab which yields a peak burning rate of 3.5 MW in the open. This time, the peak output changes from 3515 kW to 4374 kW, indeed enough to trigger flashover. Finally, FIRST was run with a slab of the same size but larger mass, so that burning could continue **past** 4374 kW. The calculation indicates that 10 seconds later, the heat output would be 7595 kW. The model indicates that the peak lies substantially above 8 MW.

Radiation Fluxes

We can estimate a relationship between the radiation flux and the flame height as follows: The burning kiosk can be considered a kind of pool fire. For pool fires, Heskestad has shown that the flame height z_f is well correlated with the convective power output $\dot{Q}_c$ according to

$$z_f \approx 0.23\,\dot{Q}_c^{2/5} - 1.02\,D \tag{3}$$

where D = 2R is the diameter of the pool fire. To a first approximation, we may take z_f to be proportional to D. Then Eq.(3) implies that

$$\dot{Q} \approx B\, z_f^{5/2}. \tag{4}$$

The mean flux seen by a flux gauge at the distance r from the fire is

$$\phi = \frac{\dot{Q}_{rad}}{4\pi r^2} \approx \left(\frac{\chi_R B}{4\pi r^2}\right) z_f^{5/2} \tag{5}$$

We tried to verify this by correlating the radiative fluxes with the flame heights. Consider the flux data for kiosk 3. The correlation is shown in figure 11. The radiometer is at a height z = 1.8 m above the floor, while the top of the door, from which the flames first emerge, was about 0.66 m above the floor. Hence $z_o = 1.8 - 0.66 = 1.14$ m. For $z_f < 1.14$, the flux is expected to be negligible; we see that this is indeed the case.

It is apparent from figure 11 that the largest concentration of readings were in the region $2.5 < z_f < 3.1$ m, $3 < \phi < 7$ kW/m^2. As the flame height increases, the flux increases, as we would expect. However, there is a puzzling distribution of points in the lower right-hand corner of the figure, corresponding to flame heights of 3.5 to 4.4 m, but where the flux reading was a low as 2 kW/m^2. Examination of the data shows that at t = 1604 s, the flux reading falls abruptly from over 20 kW/m^2 to 4.4 kW/m^2, unaccompanied by any similar drop in the RHR. The lower radiometer shows the same behavior, so that this reading was not spurious. However, that was the moment at which the superstructure collapsed -- hence the fire became several fires, spread out on the floor. This completely explains the behavior, and **shows that we must ignore these outlying points as not relevant to a correlation.**

When these outlying points, and some analogous ones at t $\approx$ 1340, were removed, the correlation improved, but not startlingly so. On the other hand, we have already noted, in examining the heat of combustion curve, that there is a phase difference between the mass-loss rate and the rate of heat release curves. By shifting the $\dot{Q}$ curve forward in time, the points are shifted into a much more nearly coherent pattern; a shift of 48 seconds raises the correlation coefficient r^2 from 0.7808 to 0.9444 (figure 12).

Another way to obtain a correlation is to assume that it is a power law. The flux was plotted logarithmically *versus* the flame height, for all five tests. When this was done, the correlation for kiosk 3 was even better: $r^2 = 0.9791$. The correlations for the other tests are equally good; however, the slopes vary, from a low of 2.3 for kiosk 5, to a high of 5.2 for kiosk 1. Why these various powers differ among themselves, as well as with the theoretically expected 5/2 power, is not clear. On the other hand, it is quite remarkable that the correlations are as good as they are, considering the complexity of the geometry and of the fires. This warrants further study.

CONCLUSIONS

1. The reason(s) for much (though not all) of the detailed burning behavior becomes clear *after* the fact -- but could not have been readily predicted, other than in a very crude way.

2. The results of apparently identical fires can differ substantially. Since the results are not "chaotic," they must be highly sensitive to initial conditions; that is, very small initial differences (in the experimental setup, initial conditions, ignition, etc). can lead to quite large differences in results. The equations describing the dynamics must be highly nonlinear and/or stiff. The most obvious probable initial difference is in the size of the opening of the kiosk doors.

3. In light of the variability of the results from the three nominally identical tests, it is essential to have a number of replicate tests; three is a minimum, and more are required in order to achieve statistically useful results.

4. As has been stated elsewhere (see, for example, [13]), this also implies that if the results of a computer run lie within the experimental limits, this must be considered to be "perfect" agreement, in the sense that agreement cannot be better.

5. Without the boxes below <u>and</u> the lower doors being opened a bit, the fire would never have "taken off."

6. As was confirmed by the runs with FIRST, the first ten minutes of burning was ventilation-limited burning in the lower box. When the doors fall off, internal flashover results, in the box.

7. In obtaining $\dot{Q}(t)$, the sum of the various time delays prior to measurement shift with the power output, and this should be taken into account in the analysis.

8. It would be naive and misleading to use the raw data; time-shifts and other adjustments must be carried out, and in such a fashion that the results are internally consistent, as well as reasonable. Thus, the mass loss rate is best found by first adjusting $\dot{m}$ to remove spurious peaks and valleys, then smoothing the "adjusted" data.

9. When the HRR curve is plotted on semi-logarithmic paper, this gives equal weight to comparable fractional increases in power output, it is easier to interpret; the curve shows several asymptotes, indicating several "stages" of burning.

10. The mass-loss rate depends on the pyrolysis rate of the solids, whereas the rate of heat release depends on the combustion rate, which depends on other factors besides the fuel supply rate. Hence what we have identified as H_c is in fact a function which depends on the (instantaneous) combustion efficiency as well as the effective heat of combustion, and the curves labeled "effective heat of combustion" really are curves of $\chi_A(t)H_c(t)$.

11. Although a 1.8 MW fire is quite fierce, it will generally not pose the risk of a flashover in a mall, since the enclosure is much larger than the one used in this experiment.

FURTHER WORK

There are a number of interesting lines of inquiry which should be pursued in the future:

1. Correlate the full-scale results with Cone Calorimeter and ICAL tests of the kiosk materials.
2. Show and analyze the results for the production of CO, CO_2, soot and smoke.
3. Discuss the temperature distribution in the enclosure, and its relation to the burn.
4. Understand why the flame-height/RHR correlations sometimes deviate from the theoretical expression.
5. Investigate any possible effects of the hood (e.g., puffing modes) in producing the peaks and valleys observed in the effective heat of combustion curve.
6. The most obvious probable initial difference in the three replicate tests is in the size of the opening of the kiosk doors. Therefore, if the experiment were to be done again, it would be advisable to drill holes in the closed doors, to get more precisely identical ventilation openings.

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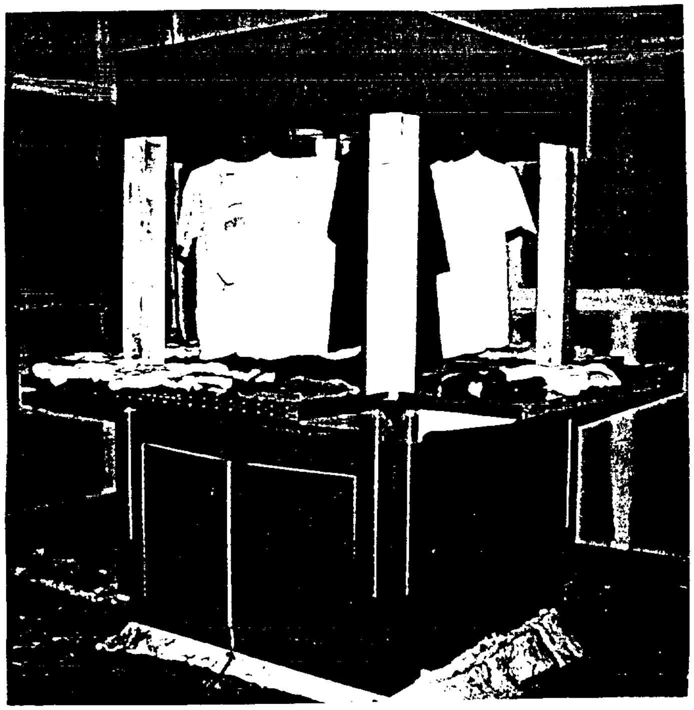

Figure 1. Photograph of the kiosk that was used, with the shelves down.

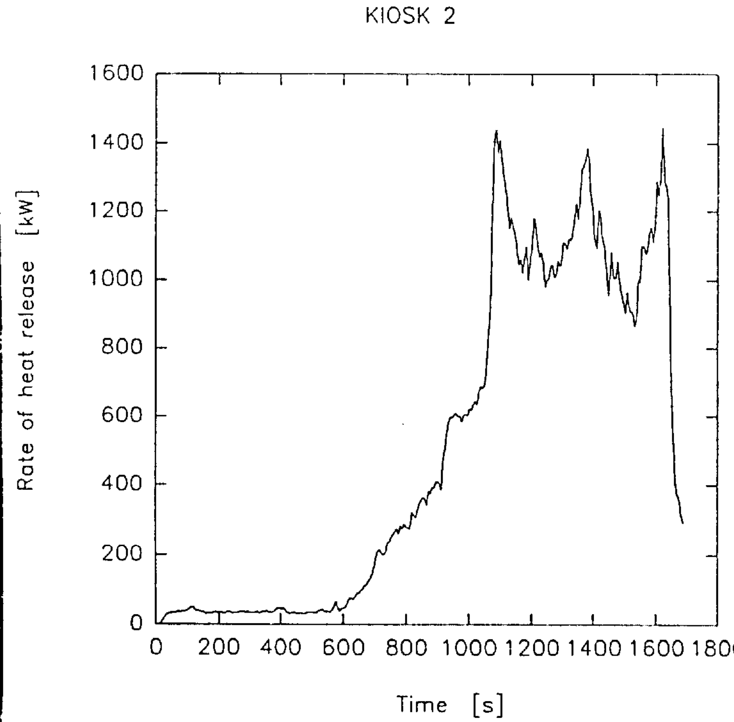

Figure 2. The heat release rate of kiosk 2, burning in the open

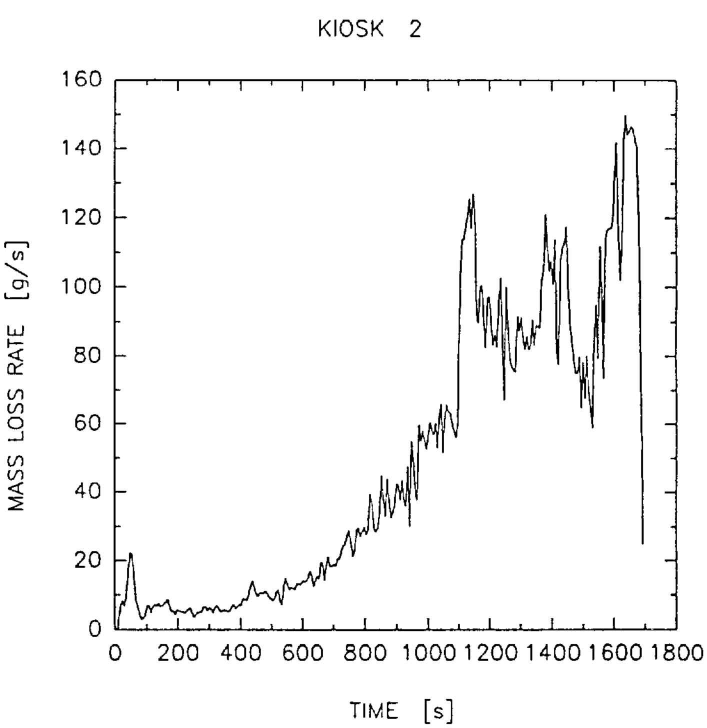

Figure 3. Mass-loss rate of kiosk 2.

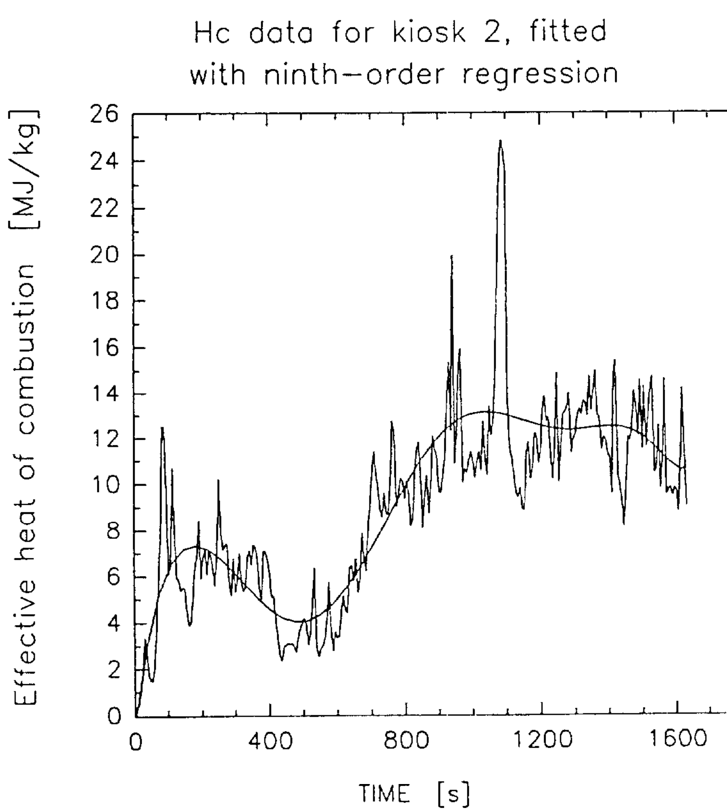

Figure 4. Effective heat of combustion of kiosk 2.

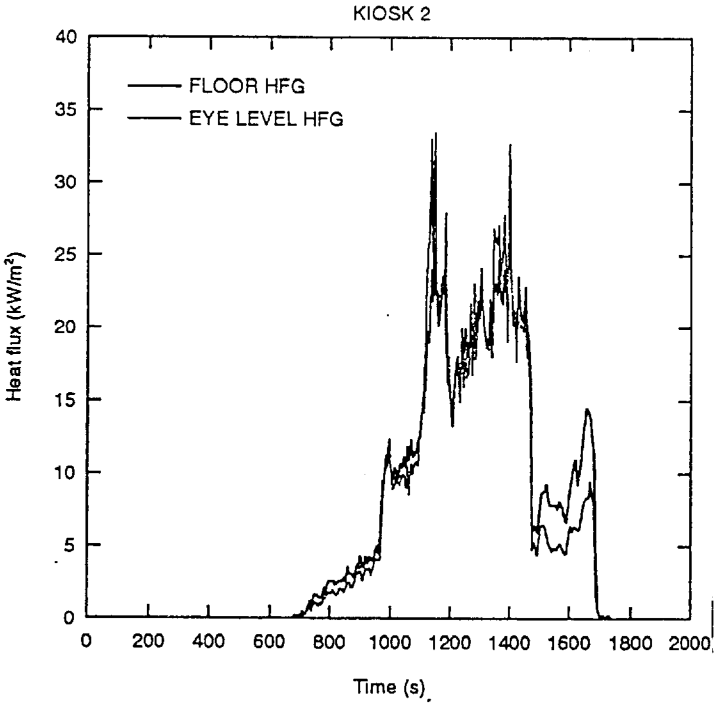

Figure 5. Radiative heat fluxes from the flames from kiosk 2.

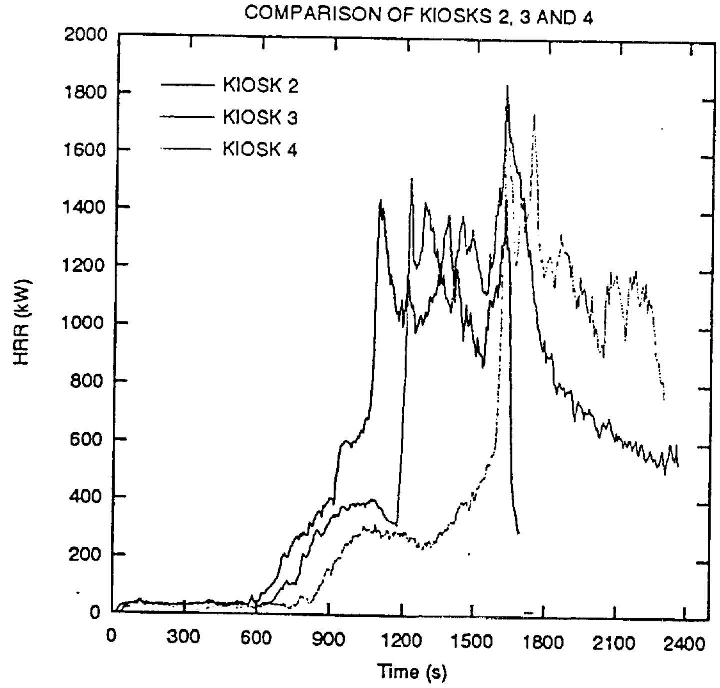

Figure 6. Simultaneous plot of the three rate of heat release curves.

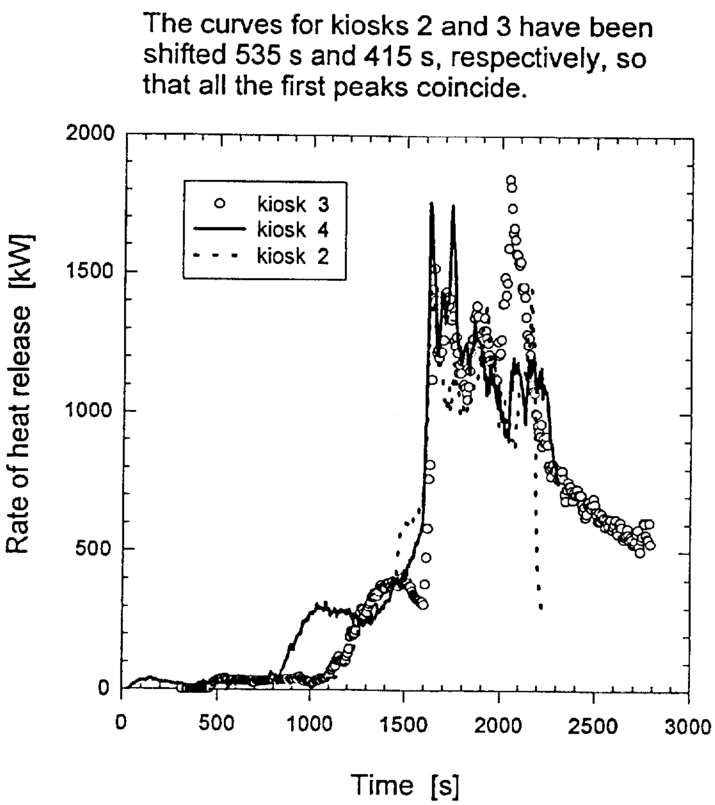

Figure 7. All three outputs, made to agree as closely as possible.

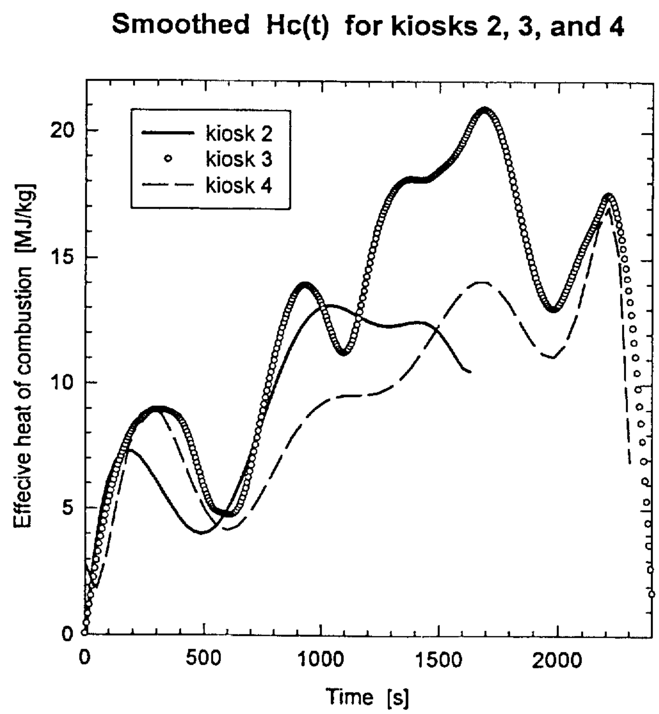

Figure 8. Effective heat of combustion for the three kiosks; the comparison is best made with smoothed values.

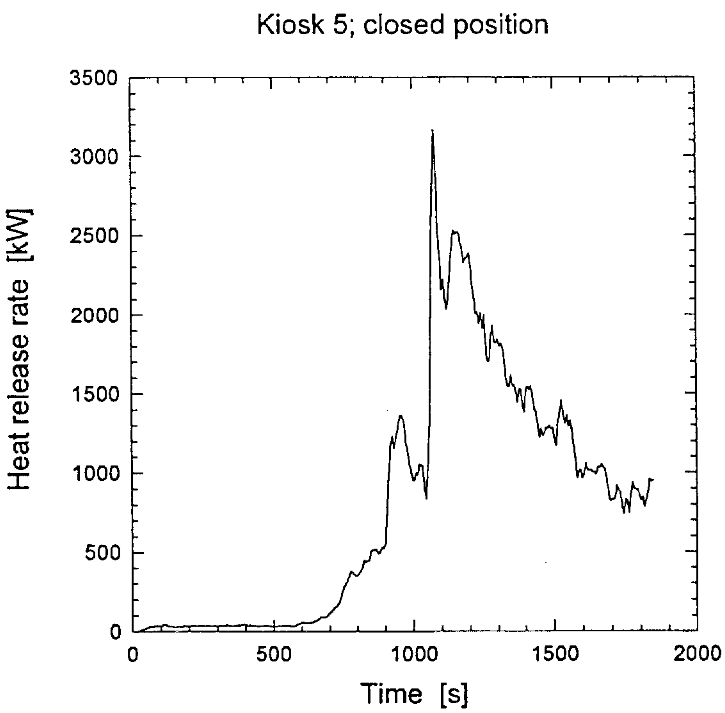

Figure 9. Rate of heat release of kiosk 5.

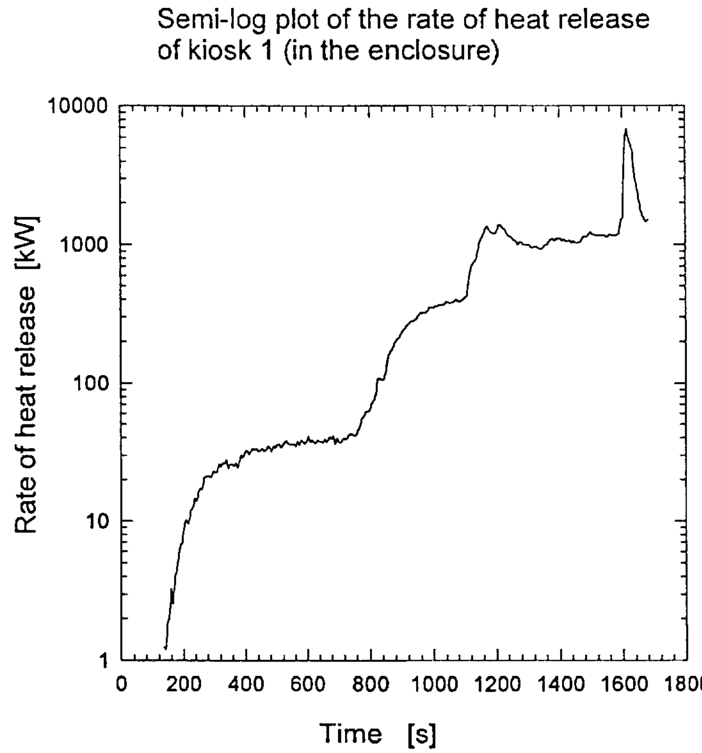

Figure 10. Semi-logarithmic plot of the rate of heat release of kiosk 1.

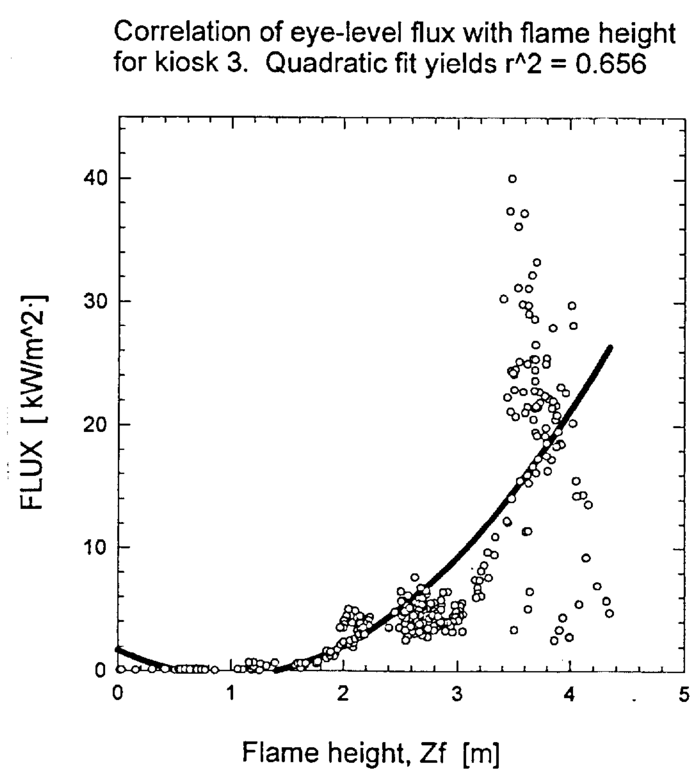

Figure 11. Flux *versus* flame height, raw data.

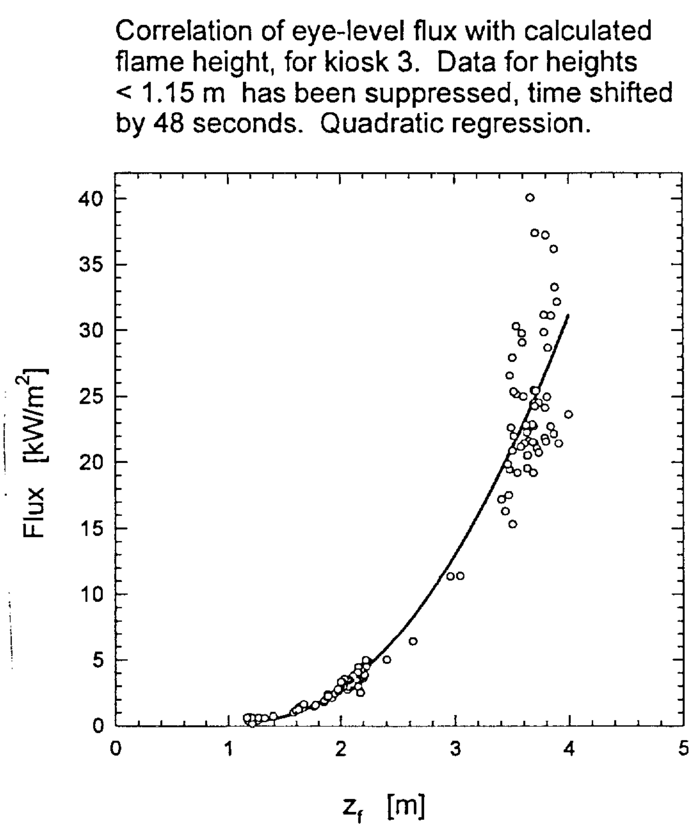

Figure 12. Flux *versus* flame height, adjusted data.

Discussion

Ronald Alpert: You implied that if those small doors at the bottom had been fully closed, there would have been no flaming. Did you verify that?

Henri Mitler: No.

Walter Jones: These experiments were done last summer. Subsequent to that, NIST had its Annual Fire Conference in Orlando in conjunction with SFPE. During that conference, such a fire occurred in a shopping center about two miles from where we were holding the conference. It was not done for our benefit, so we did not have any instruments to make measurements. But indeed, the case in point was a kiosk for selling cotton t-shirts that had been closed up for the night. The ignition was from an electrical fixture on high as opposed to low, but it's equivalent to the electrical tape. Since we did not have any measurements, we don't know the size of the fire, but it was sufficient to turn on sprinklers that were between 20 and 40 feet above the kiosk, thus indicating that the fire was on order of megawatts and that they do happen in real life. Our intention with these experiments is to try to have sets of fuel packages that occur in real situations.